HA-2259

PROGRESS REPORT NO. 35

DEVELOPMENT OF ULTRAHIGH STRENGTH, LOW DENSITY, ALUMINUM PLATE COMPOSITES

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TORRANCE, CALIFORNIA

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Progress Report No. 35

DEVELOPMENT OF ULTRAHIGH STRENGTH LOW DENSITY, ALUMINUM PLATE COMPOSITES

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George C. Marshall Space Flight Center
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ABSTRACT

The objective of this project is to develop methods for producing and to establish techniques for joining aluminum alloy plate and sheet composites reinforced with steel wire with a target tensile strength of 175,000 psi and a maximum density of 0.144 lbs./cu.in.

Sample sizes range from 0.023" to 3/4" thick and 16 sq.in. to 8 sq.ft. in area. Room temperature strengths up to 175,000 psi at a density of 0.144 lb./cu.in. have been attained. At -320^{o}F an increase of 20% in tensile strength was obtained. V-notched Charpy impact strength increased from 12 ft.lbs. at room temperature to 18 ft. lbs. at -320^{o}F. Notched tensile test specimen K_t6 tests resulted in notched-unnotched ratio of about 0.95. One beryllium sample, 49% 2024-0/51% Be, was tested in tension: UTS of 87,500 psi was achieved. A boron fiber 25% in 2024 aluminum matrix tested at 104,000 psi UTS.

Joints produced by overlapping modules and by liquid infiltration have resulted in efficiency of 92 and 54%, respectively.

The effect of cold work and heat treatment on the composite stress strain curve and the basis for composite efficiency is discussed.

The current effort is directed principally toward improvement of fabrication techniques for the full size plate, with continuing work on joining and other secondary fabrication methods; fabrication of sheet; hot rolling plate; wire distribution; and testing composite samples at temperatures from -423^{o}F to 80^{o}F.

TABLE OF CONTENTS

I. ACCOMPLISHMENTS PREVIOUSLY REPORTED

A. General

The original literature and industrial survey was reported in HA Report Number HA-1955, dated August 30, 1963. Annual reports HA-2059, July 1964, and HA-2166, July 1965, cover the work accomplished during the previous years and up-date the literature survey.

B. Summary

1. Selection of Materials

Screening tests were conducted with the following listed steel wire and aluminum alloy matrix:

Steel Wire	Aluminum Matrix		
Carbon steel rocket wire	1100	2219	2024
NS355	5052	5456	7075
NS302	7178		
AFC 77	No.12 Brazing Sheet		

Most of the samples were produced using NS355 type wire. AFC 77 exhibited the highest strength (520-560 ksi) after elevated temperature (900°F) cycle; however, only small quantities are immediately available. Carbon steel rocket wire was used initially but was discontinued when it became desirable to fabricate at temperatures in excess of 400°F.

Aluminum alloy 2024 was selected for the matrix alloy as it offered the strongest matrix material consistent with other requirements. No difficulty was experienced with the other listed alloys, with the exception of No.12 Brazing Sheet, which exhibited some evidence of decreasing the strength of the NS355 wire.

2. Fabrication Methods

a. The following methods of distributing the wire in the aluminum matrix were investigated:

Warm Extrusion
Hot and Cold Pressing
Hot and Cold Rolling

b. The results to date indicate that hot pressing is the most economical method for producing plate, and that hot rolling is the best method for producing sheet or tape modules to be used for producing formed shapes.

3. Fabrication of 1/4" x 12" x 96" Plate

Four 1/4" x 12" x 96" plates have been produced by progressive hot pressing. The as-produced plates are thicker in the center than on the edges resulting from spring in the high speed steel dies. The best method for overcoming the crown in the plate is hot rolling at 800°F. The second plate produced was hot rolled from 0.290 to 0.265-inch with resulting improvement in flatness.

4. Fabrication of 12" x 96" x 0.035" Sheet

a. Six sheets nominal 0.035" x 12" x 96" were produced using the same procedure as for the 1/4" thick plate of the same size.

b. After fabrication by progressive hot pressing, the sheets were hot rolled to improve flatness and physical properties. See Section 7, Table V.

c. Excessive wire breakage was experienced in laying up the sheets. This problem was experienced with the first 1/4" plate and did not re-occur in the second and third plates after drag on the spools was increased and wire flow smoothed out. Since the drag on each wire through the entire system is about two pounds, and it takes 30 pounds to break a wire, it is evident that a severe malfunction must occur to cause a wire to break. Observation of the operation and consultation with the wire producer led to the conclusion that the breakage was caused by a form of backlash of the wire on the spools resulting from wire loosening on the spool. It is felt that separating the spools with keyed plastic washers in conjunction with rubber rollers to keep constant tension on the wires will alleviate the problem.

d. The sheets were fabricated from three sheets of 2024 aluminum and two layers of wire. The wire breakage and attendant tying off of the broken wire caused uneven wire distribution with resulting uneven sheet surface. Results of thickness measurements on the sheet in the as-pressed and after-rolling conditions are tabulated below:

Condition	High	Low
As-pressed	0.038"	0.025"
After 3 roll passes	0.032"	0.026"
After 6 roll passes	0.031"	0.027"

e. Prior to fabricating the 12" x 96" sheet, a trial piece 0.023" thick consisting of two pieces of 2024 aluminum and one layer of 0.009" wire was produced. The wire loading was 20%. Tensile tests for this sheet follow:

Condition	UTS (psi)
As-pressed, Solution Heat Treated and Aged	145,000
Annealed 6 hours at 800°F	143,300
Annealed 8 hours at 800°F	132,500
Annealed 12 hours at 800°F	128,600
Annealed 8 hours at 800°F, Cold Worked 2%	146,000

5. Bonding

a. The investigation of bonding has been divided into two areas:

aluminum to aluminum
aluminum to steel wire.

The best results with aluminum to aluminum bonding have been obtained by diffusion bonding the matrix at 900°F and 14,000 psi. Regarding steel wire to aluminum bonding, a good mechanical bond has produced the highest efficiency in the composite sample (95-100% of the law of mixtures). Formation of an alloy layer between the aluminum and steel wire reduced the UTS of the composite by 40%.

b. A metallographic study of the 1/4" x 12" x 24" and the first three 1/4" x 12" x 96" plates was started to determine the effect of the scale-up on the integrity of the composite. The following tentative conclusions have been reached:

1) The bunching of wires in the 1/4" x 12" x 96" plates adversely affects the bonding because of non-uniform metal movement.

2) The additional 2% cold rolling received by the third 1/4" x 12" x 96" plate resulted in gross cracking in the plate.

3) Although the bonding and wire distribution was much better in the 12" x 24" plate than in the 12" x 96" plate, any effect of this difference was not reflected in the tensile properties, which would indicate that it is being masked by the other variables involved.

c. To investigate the effect of added time at temperature on bonding, some 0.023" sheet consisting of two sheets of 0.010" 2024-0 aluminum and one layer of 0.009" NS355 wire was fabricated using the same procedure as for the 1/4" x 12" x 24" plate. Diffusion over the bond line was completed in eight hours at 800°F.

6. <u>Secondary Fabrication</u>

a. The following operations have been successfully performed on composites of 25 percent by volume steel wire in aluminum matrix. Electron beam welding, both longitudinal and transverse to the direction of reinforcement, and the use of steel inserts for effecting joints were not successful.

1) Hot rolling (10%) to improve flatness.
2) Cold rolling (2%) to improve physical properties.
3) Diffusion bonded joints (92% efficient); infiltration (54%).
4) Resistance spot welding of sheet.
5) Elox machining.
6) Abrasive saw slotting.
7) Metal spraying for protection of exposed composite edges.

7. Mechanical Properties and Samples Tested

The samples tested to date have led to the following observations:

a. The ultimate tensile strength achieved in the composites tested is determined by the tensile strength of the wire and the proof strength of the aluminum matrix at the limit of elongation of the wire.

b. If there is no load transfer between the wire and the matrix, the bundle strength of the wire only is realized.

c. The ultimate tensile strength of the composite is increased when the strength of the matrix is increased by heat treatment and working, provided the wire is not adversely affected by the operation.

d. The yield strength (0.2% offset) of a 2024 sample containing 19.2% NS355, 0.010" steel wire was increased from approximately 70,000 psi to 120,000 psi by cold rolling (from 0.115" to 0.107") within one hour after solution heat treatment; i.e., the 70,000 psi Y.S. sample was -T6 and the 120,000 psi Y.S. was -T3. Since the increase in yield strength is greater than is to be expected from a change from -T6 to -T3 condition of the matrix, it is felt the additional yield strength is coming from an autofrettage effect.

e. Three 1/4" thick samples were pulled in tension, indicating a tensile strength of 137,000 psi, which calculates to be 94% efficient, using the strength of wire as 450,000 psi and the as-pressed 5456 as 49,000 psi.

1) The first sample tested indicated a modulus of 11.2×10^6 psi.

2) The second sample was loaded in cululative increments of 3000 pounds; the load was released to 100 pounds prior to adding the next increment. The modulus for successive increments was:

(a) - 9.8×10^6
(b) - 15×10^6
(c) - 15×10^6
(d) - 15×10^6
(e) - 15×10^6

3) The third sample was strained beyond the change in slope of the stress strain curve and then released. This gave modulii of:

(a) - 9.0×10^6
(b) -- 15.1×10^6
(c) - 17.7×10^6
(d) - 13.1×10^6

4) Since the calculated modulus (on a basis of area) is approximately 15×10^6 psi, it is felt the low modulus is a result of the aluminum being in tension after hot pressing and that this condition is corrected by plastically deforming the aluminum so that the stresses are reversed.

f. In samples with UTS's over 130,000 psi, there is a tendency of the specimen to crack at the shoulder when tensile tested. This difficulty is overcome by increasing the shoulder radius to 1-1/2".

g. Results of some screening tests on the first 1/4" x 12" x 96" plate are listed below:

Condition	UTS (psi)
As pressed	150,000
SHT, CW 2%, Aged	159,000
SHT, CW2%, Aged, CW 2%	161,000

(Table continued on following page)

Condition	UTS (psi)
Thermally cycled, 8 times (212°F H_2O - Liquid N_2)	157,700*
SHT, Aged, Test -100°F	158,000
SHT, Aged, Test -200°F	173,000
SHT, Aged, Test -320°F	210,000

*Additional tests will be performed to determine whether the apparent loss in strength is due to thermal cycling or falls within the normal strength variation.

h. When estimating the expected strength of 2" x 8" composite samples, with all the reinforcing wire coming from one spool, the simple law of mixtures (i.e., strength of wire times its area plus strength of matrix at composite strain time matrix area) gave strengths in good agreement with test results. In the case of the 1/4" x 12" x 96" plate, when 43 spools of wire were used, the question arises as to what strength should be assigned to the wire. Some of the possibilities are as follows:

The aluminum matrix was etched out of the two-inch gage length of a Standard ASTM sample cut from 1" x 8" section of the first 1/4" x 12" x 96" composite plate, exposing the reinforcing wires. The sample was loaded to failure and results along with estimations of the calculated load based on the average strength of the wire (491,000 psi) in the plate, the lowest strength wire (476,000 psi) in the plate, and the statistical bundle strength of the wire in the plate are listed below:

	Load	% Sample
1) Etched out sample	12,850 lbs.	100
2) Average strength per wire in plate x number wires in sample	13,105 lbs.	102
3) Lowest strength wire in plate x number wires in sample	12,640 lbs.	98.4
4) Statistical bundle strength of wires in plate*	12,240 lbs.	95.3

*See HA-2208 for method used.

i. The series of samples shown in Table I were run to determine the effect of strength of the matrix on the properties of the composite. However, variations in the wire mix and variations in cold work, because of sample flatness, have masked to some extent the effect of cold work and heat treatment. For comparison see Table II.

TABLE I

Number	Condition		Tensile Strength (psi)		Remarks
	Annealed	CW Nominal	Actual	Corrected* to 25% Wire	
1	"	No work	145,000	142,700	-
2	"	1% CW	145,000	147,300	-
3	"	2% CW	149,500	147,100	-
4	"	3% CW	141,000	144,000	Broke outside gage marks
5	"	4% CW	150,000	152,300	-
6	SHT,Aged	No work	147,000	149,000	-
7	"	0.8% CW	161,000	161,900	-
8	"	1% CW	169,500	175,000	-
9	"	1.4% CW	157,500	160,900	Broke in grip
10	"	2%	156,000	166,800	-

*In the first plate, wire density variation resulted from wire breakage during lay-up. Corrections are based on density measurements.

j. The tensile tests reported in Table I (page 8) were repeated using samples which were cut longitudinally from the first 1/4" x 12" x 96" plate. All of the samples in the annealed condition came from the same strip and all samples in the heat treated condition came from one strip. Results obtained are reported in Table II and indicate what may be expected in improvement in UTS by heat treatment and cold work for this system.

TABLE II

Number	Condition		Tensile Strength (psi)	Remarks
	Annealed	CW Nominal		
E2	"	No Work	135,000	Bar broke outside gage marks
E3	"	1%	143,000	" " "
E4	"	2%	141,000	" " "
E5	"	3%	146,900	" " "
E6	"	4%	145,600	" " "
D2	SHT,Aged	No Work	162,100	" " "
D3	"	1/2%	162,500	" " "
D5	"	1%	165,000	-
D6	"	1-1/2%	166,000	-
D7	"	2%	170,000	" " "

k. Four notched tensile specimens were tested in tension. It was not possible to obtain the 0.00147 root radius so the K_t value for the radius as produced was taken from "Stress Concentration Design Factors - by R. E. Peterson - Figure 17." Results are listed in Table III.

TABLE III

Sample	K_t	UTS	*UTS (Corrected to 25% Wire)
1	6.3	152,000 psi	143,600 psi
2	6.2	157,000 psi	152,600 psi
3	6.3	166,000 psi	158,700 psi
4	7.3	159,000 psi	150,800 psi

*Sample strength corrected to 25% wire by density measurement.

Samples in Table III were in the solution heat treated, cold worked and aged condition. Because of the other variables known to exist, an exact comparison with unnotched samples is not possible. However, on an average it would appear that the notched samples are testing 10 - 15,000 psi less than the comparable unnotched ones.

1. Seven Charpy subsize Type A impact specimens were tested. Results are reported in Table IV.

TABLE IV

Temperature	Ft. Lbs.
R.T.	11.5 13.0 12.0
-97°F	14.0 14.0
-320°F	18.0 18.0

The results compare favorably with the Handbook (ASM 1948) "Charpy V-Notch Impact Values" given for 2024-T4 for 75°F and -110°F; 13 ft. lbs. and 16 ft. lbs., respectively. The samples were cut from the first 1/4" x 12" x 96" plate.

m. Table V gives the results of tensile tests on one of the six 1' x 8' x 0.035" sheets produced, in the as-pressed and rolled condition. The aluminum was etched from several samples and no indication was found of wire breakage at other than the fracture point.

TABLE V

Ultimate tensile strength in psi for samples from
1' x 8' x 0.035" sheet in as-fabricated condition

Condition	a	b	c	d	e
As pressed	121,000	129,000	132,000	128,000	125,500
As pressed plus 3 roll passes	148,500	138,500	107,100*	145,000	120,000
As pressed plus 6 roll passes	155,500	132,000*	117,000*	130,500*	148,500

* Broke in grips.

n. Results of tensile test of samples cut from the first 0.035" x 12" x 96" sheet in the solution heat treated and aged condition are given in Table VI.

TABLE VI

Tensile Strength in ksi of 1' x 8' Sheet
Hot Rolled, Solution Heat Treated and Aged

Sample	a	c	d	h	i
4					
UTS	154	134	142	*127	138.5
% Wire	23.5	19.9	22.4	-	19.3
25% Wire**	162	157	153	-	164
5					
UTS	142	140	145	*141	*144
% Wire	21.6	21.1	21.6	-	-
25% Wire**	158	157	160	-	-

*Broke in grips.
**Strength adjusted to 25% wire.

o. Two samples were cut from plate No. 2 (1/4" x 12" x 96"). The first after hot rolling 5% and the second after hot rolling 10%. Results were 139,000 psi and 150,000 psi, respectively. The stress strain curves were similar to those for the annealed condition and no adverse effects from the rolling operation were indicated. Removal of the matrix by etching revealed no damage to the reinforcing wires from the rolling operation.

p. The effect of heat treatment and cold work on the stress strain curves of 25% 0.009" NS355, 75% 2024 aluminum composite are presented in Figure 1. Six curves are given, as listed below:

1) 2024-T6, handbook data
2) 25% steel-aluminum composite - Sample E2
3) 25% steel-aluminum composite SHT & Aged - Sample D2
4) Theoretical (law of mixtures) 25% composite; i.e., 25% curve 6, 75% curve 1.

5) 25% steel-aluminum composite SHT & Age, Cold work 2% - Sample D7
6) NS355, 0.009" wire - National Standard

Curve 4 is an idealized curve; i.e., it assumes the wire and matrix behave the same way in a composite as they do separately.

q. A sample of boron fiber (48.5% in 1100-0 aluminum matrix tested at 104,000 psi UTS. Sample size was 1" x 8" x 0.070".

r. A sample, 1/4" x 2" x 0.050", was made of boron fiber and 2024 matrix containing nominal 25% B. The sample tested in tension failed at 104 ksi.

s. One sample of 0.010" beryllium in 2024-0 aluminum alloy matrix was fabricated with 49 volume percent wire. The sample was 7/8" x 8" x 0.020" and the tested UTS was 87,500 psi for a law of mixture efficiency of 93%.

The Effect of 2% Cold Work on 25% NS355 2024 Aluminum Composites.

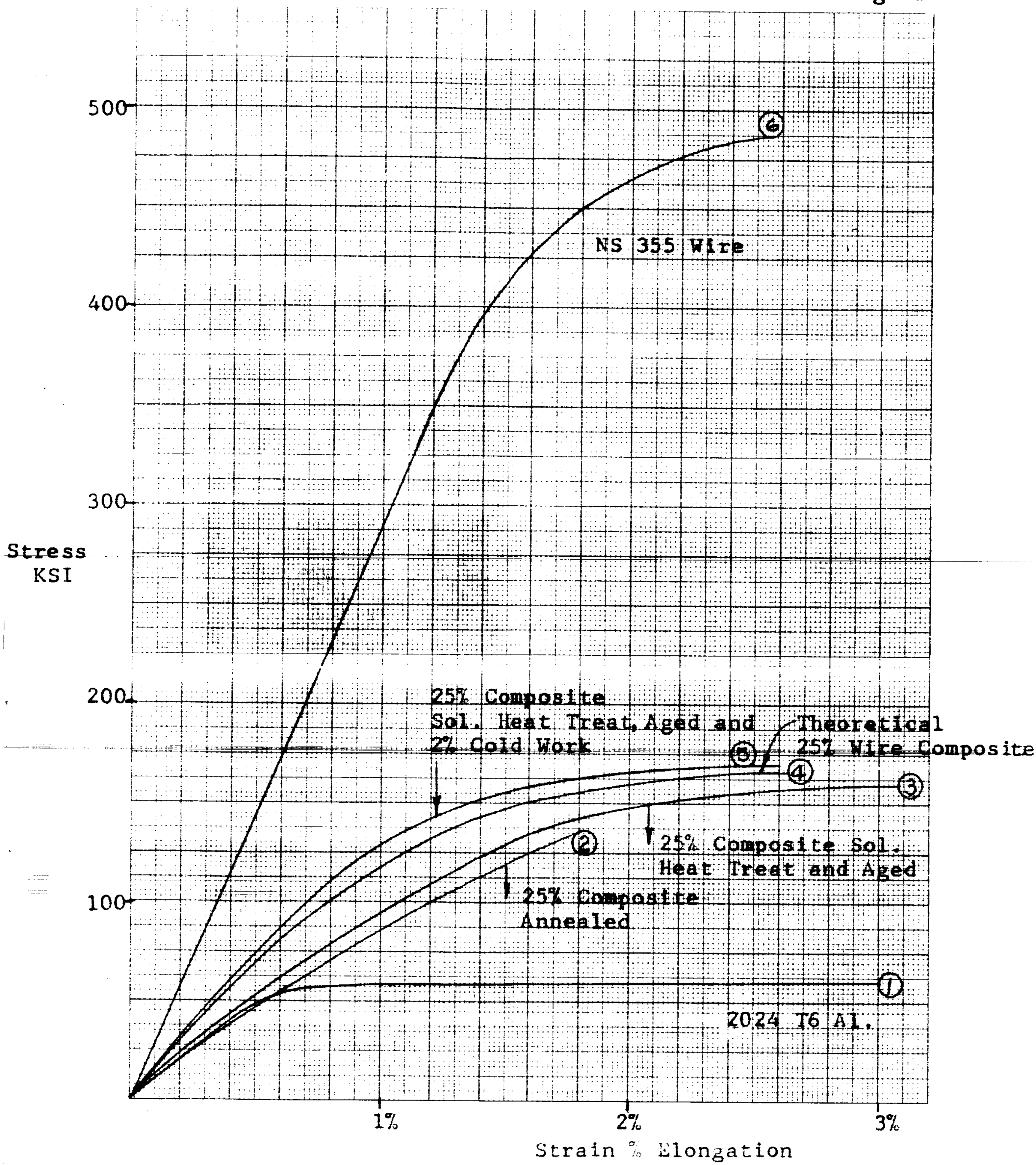


Figure 1

II. ACCOMPLISHMENTS DURING THIS REPORTING PERIOD

A. Summary

1. Strength of matrix alloy blanks is discussed.

2. Sketches of sub-standard samples for test at $-423^{o}F$ are shown.

3. Preliminary work at Midwest Research Institute on electrothinning of composite samples for observation in transmission in the electron microscope is presented.

B. Composite Strength and Efficiency

There are several methods of computing the tensile efficiency of the composite which depend on how you define the constituted properties. In this work we have used the best properties available of the constituent materials as the basis, calculating percent efficiency; i.e., the average strength of the NS355 wire used in the first 1/4" x 12" x 96" plate was 490,000 psi and the highest strength to be expected from 2024 aluminum matrix at 2% elongation is 70,000 psi. Therefore, if we obtain proportional contributions from each constituent we should achieve an Ultimate tensile strength of 175,000 psi. In sample D7, Table II, 170,000 psi was achieved for an efficiency of 97%.

As a check on the matrix, 2024 blanks were run during fabrication of the 1/4" x 12" x 96" plate. Results are given in Table VII.

TABLE VII

2024 Diffusion Bonded Sheet, No Wire

Condition	UTS (psi)	UYS (psi)
As Fabricated	33,300	17,300
Annealed	28,300	14,600
SHT and Aged	54,600	36,700
SHT, CW, Aged	57,000	41,000

These matrix samples were processed using the same procedure as used for the composites. The result for the annealed condition is in reasonable agreement with expected properties for this condition, whereas the results for the heat treated and heat treated and cold worked are low. The lower than expected results are most likely due to warm quench (used on composites to prevent cracking) and lower working hardening in the blanks over the composite matrix. However, it does point out the difficulty in using blank samples in figuring composite efficiencies; i.e., if the contribution of the aluminum is calculated from blank matrix material processed parallel with the composite, the calculated strength would be 155,500 psi for an efficiency of 109%, which is misleading.

C. Sub-Size Tensile Test Specimens

Drawing 11-50835 exhibits the configuration of the subsize tensile test specimen for testing at -423°F. The notch was calculated for K_t6. Dimensions were obtained from Figure 17 - Stress Concentration Design Factors by R. E. Peterson.

D. Bonding

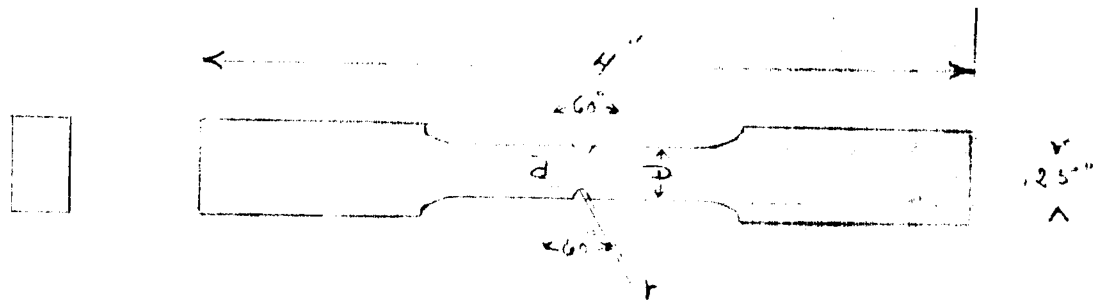
A sample composite of 25% NS355 wire and 75% 2024 matrix was furnished to Mr. Walter Trapp, AFML. A portion of this sample was used by Midwest Research Institute to develop a method for electrothinning composite specimens for observation in transmission in the electron microscope. Their work is directed toward studying dislocation arrangements in deformed composites as a function of the distance from the filament-matrix interface. Preliminary results indicated a mechanical bond between the aluminum matrix and the NS355 wire.

E. Man-Hours Expended

During this reporting period 74.0 man-hours were expended:

Engineering 81% Reporting 19%

11-50835



$D = 0.25''$

$d = 0.175''$

$r = 0.0025''$

ITEM NO.	NO. REQ.	SIZE	DESCRIPTION	ARMY	NAVY
		Full			
		MATERIAL		MATERIAL SPECIFICATION	

G = GRIND
// = SMOOTH MACHINE
/ = MACHINE
R/ = ROUGH MACHINE

FINISH

HEAT TREAT

LIMITS UNLESS OTHERWISE SPECIFIED
.X = ± .06
.XX = ± .03
.XXX = ± .005
.XXXX = ± .0005
ANGULAR ± ½°

SCALE

APPROVED	Hw	6-11-66
PRO. ENG.		
STRESS		
CHECKED		
DRAWN BY	[illegible]	6-11-66

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NO. REQ.	NEXT ASSEM.	MODEL

LET	CHANGES	DATE	BY	APP.

ACT. WT	ISSUE DATE	ISSUE NUMBER
CALC. WT		

Sub Size Tensile Test Spec[illegible]

DWG. NO.
11-50835

FORM 10001-A-3-60

III. ANTICIPATED WORK FOR NEXT REPORTING PERIOD

It is expected that the effort during the next reporting period will be directed as follows:

1. Preparation of Third Annual Report.

2. Preparation of the fourth 1/4" x 12" x 96" plate and 0.035" x 12" x 96" sheet for shipment to contracting officer's representative.

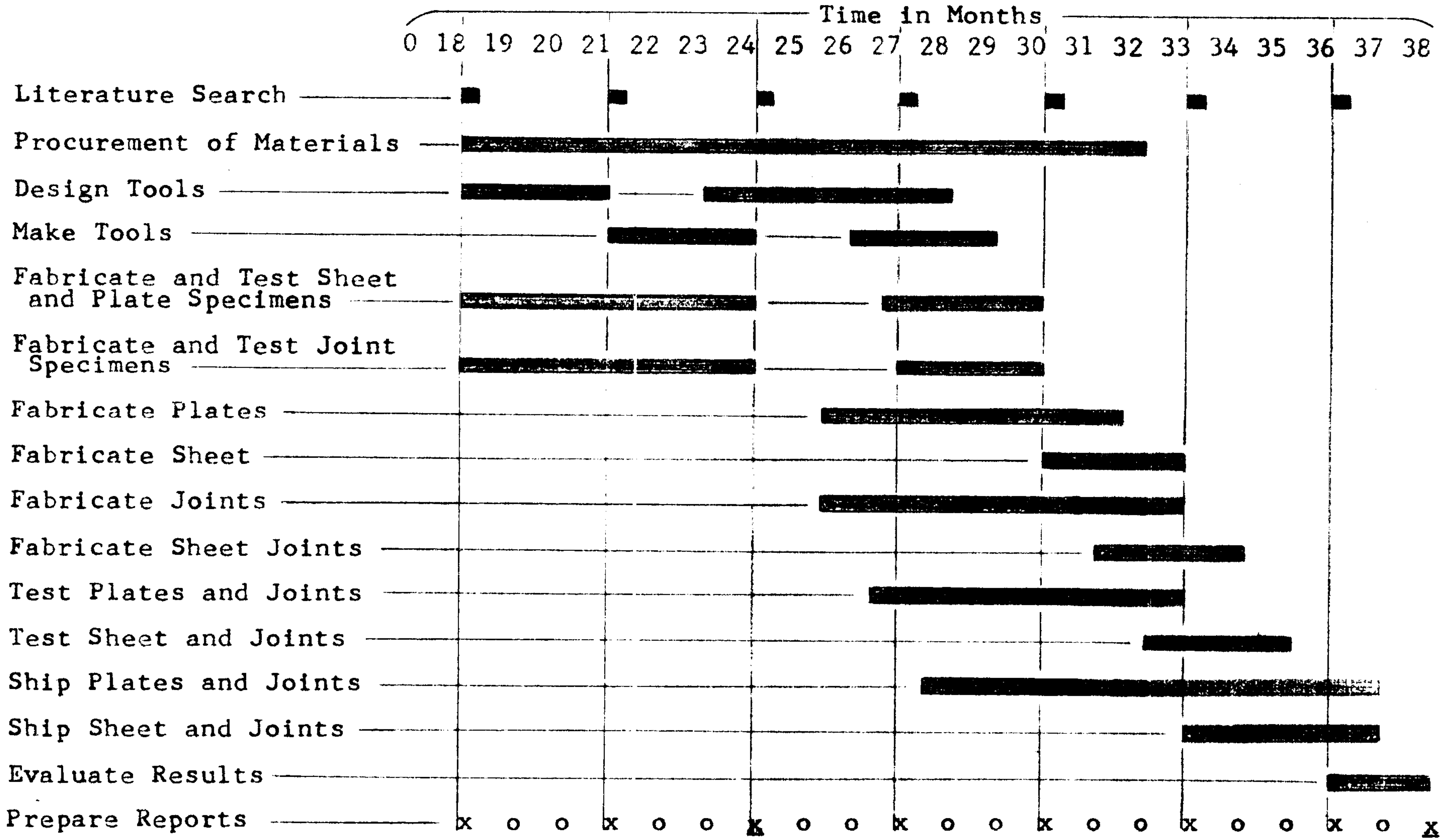
3. Preparation of 1/4" x 1/4" x 4" samples for test at -423°F.

IV. PROGRAM SCHEDULE AND PROBLEMS ENCOUNTERED

Changes in the program schedule are as indicated on the following page.

Delivery of plates, sheets and joints has been extended to August 1966.

PROGRAM SCHEDULE
(Revised)



Monthly Reports - o
Quarterly Reports - x
Annual Reports - x

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Mr. G. T. Murray, Vice President Materials Research Corporation Orangeburg, New York 10962	19

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Mr. Walter J. Trapp Chief, Strength and Dynamics Branch (MAMD) Air Force Materials Laboratory Wright-Patterson Air Force Base, Ohio 45433	21

APPENDIX

ANNOTATED BIBLIOGRAPHY

COMPOSITES

Avco Corporation, Wilmington, Massachusetts (T. Vasilos and E. G. Wolf)
"Strength properties of Fiber Reinforced Composites"
Journal of Metals, May 1966

This paper discusses composite strength of three composite types:

(1) Metallic fiber-metallic matrices
(2) Ceramic fiber-metallic matrices
(3) Refractory fiber in ceramic matrices

The uniform strain concept, strength of fiber bundles, discontinuous fibers, fiber orientation, fiber spacing, and strength-time dependance factor are covered. Summaries of metal fiber-metal matrix and ceramic-fiber-metal matrix are presented. (69 references)

MATERIALS

Space Science Laboratory of the General Electric Company, Valley Forge, Pennsylvania (L.R.McCreight, H.W.Rauch,Sr. and W.H.Sutton)
"A Survey of the State of the Art of Ceramic and Graphite Fibers" - Contract AF 33(615)-1618
AFML TR-65-105- May 1965

This report is based on a review of 500 references, 200 patents and 60 contacts, and covers: 1) the potential strength of fibers and factors affecting their strength; and 2) application of fibers. 379 pages.

PROCESSES

British Welding Journal, March 1966 (M. H. Scott and I. F. Squires)
"Metallurgical Examination of Aluminum-Stainless Steel Friction Welds"

An investigation was made into the behavior of friction welded aluminum-stainless steel samples after room and elevated temperature exposure. Strengths fell rapidly with growth of a diffusion layer of Al, Fe, Cr and Ni. Welds were stable at 400°C for 18 months. Welds become brittle at 450°C for 12 months, 500°C for 8 hours and 600°C for 15 minutes. Welds were subjected to tensile tests, metallographic examination, electron probe micro-analysis, and X-ray diffraction analysis.

Automatic Welding, No. 3, 1965 (A. S. Gel'Man) - Courtesy of the British Welding Research Association, Cambridge.
"The Nature of Friction Welding"

The nature of the processes taking place at the contacting surfaces during pressure and friction welding are discussed. Process parameters: pressure, temperature, percent deformation, time, environment, are covered for both low temperature slow movement friction welding and high temperature high rotational speed welding.

PROCESSES

Hexcel Products, Incorporated, Berkeley, California
(B. R. Garrett, G. F. Blank, A. J. Ranadive)
"Broad Applications of Diffusion Bonding"
Contract NAS7-273. NASA CR 409, March 1966

A literature survey of the present status of diffusion bonding was conducted and the information incorporated in this report. The material is divided into the following areas:

The Potential of Diffusion Bonding
Diffusion Theory
Diffusion Bonding Fundamentals
Status of Diffusion Bonding
Application of Diffusion bonding

77 cited references and 117 general references are given. A summary of practical applications of diffusion bonding techniques is given in four sections: 1) Yield stress controlled bonding, 2) Diffusion controlled bonding, 3) Creep controlled bonding, and 4) Transient melt diffusion bonding.

A summary of experimental data on diffusion bonding of similar metals (18 pages) - Base materials, Mo, Cb, Ta, W, Ni, Ti, Be, Cr, Co, Al, Fe, U-Pd alloy, Zr - and a summary on dissimilar materials (4 pages) is given.